



# Automated Registration of Multi-mode Nondestructive Evaluation Data

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SPIE Smart Structures and Nondestructive Evaluation, 13 March 2023, Long Beach CA

# Outline

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## 1. Registration cases & datasets

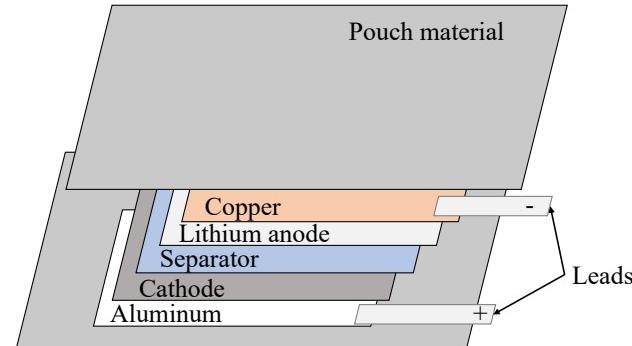
- Lithium-metal (Li-metal) pouch cells
- Additive manufacturing fatigue specimens

## 2. Image registration approach

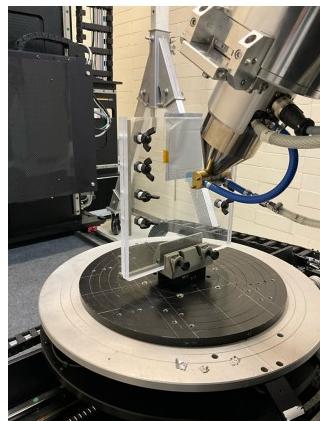
## 3. Registration results

- Li-metal pouch cells
- Additive manufacturing porosity

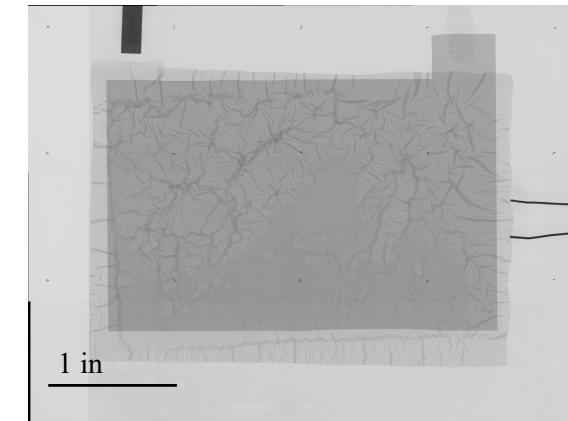
# Registration case #1: Li-metal batteries



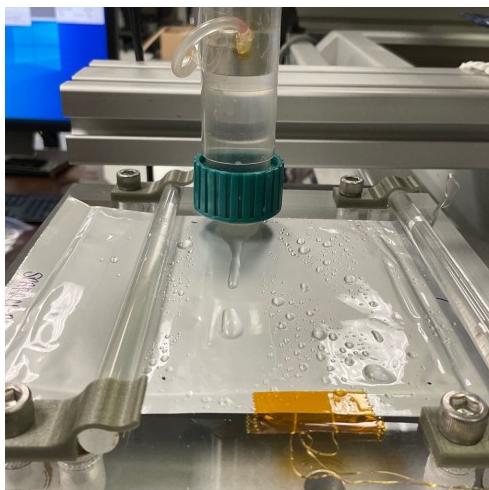
Material layup



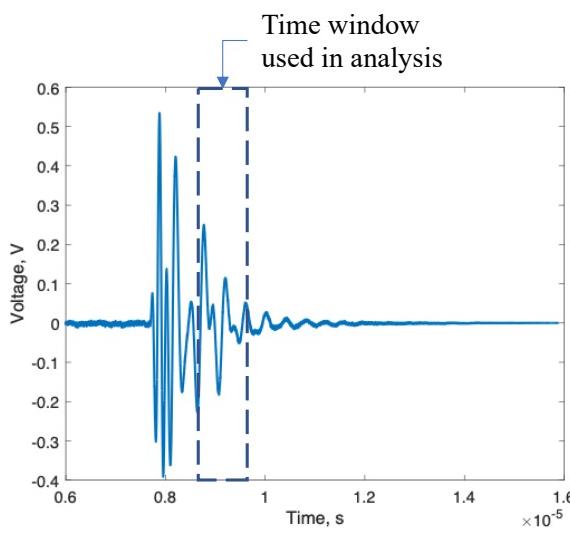
X-ray system



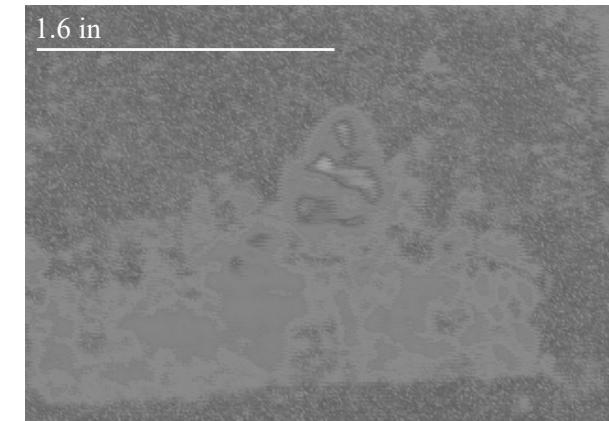
Composite digital radiograph (DR)



Ultrasonic (UT) nondestructive evaluation (NDE)  
using captured water column

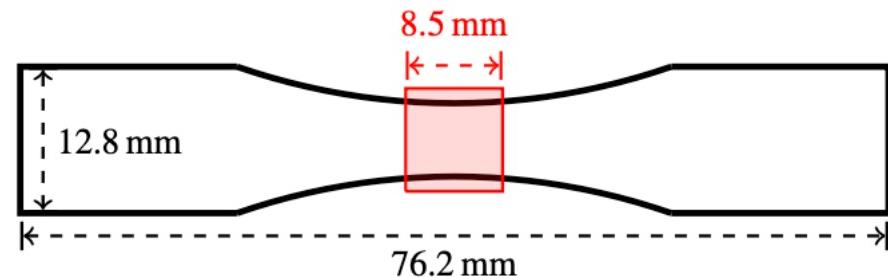


Representative UT waveform

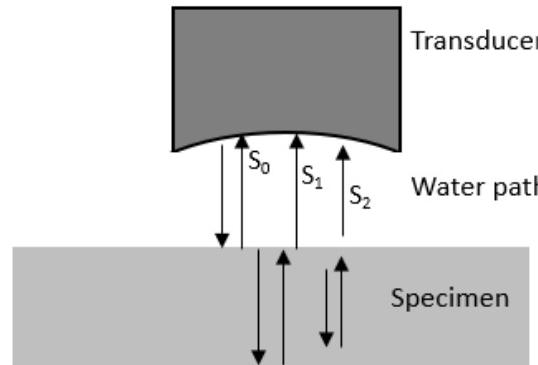
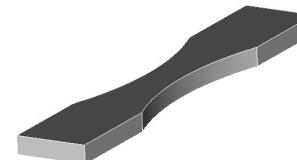


C-Scan of pouch cell

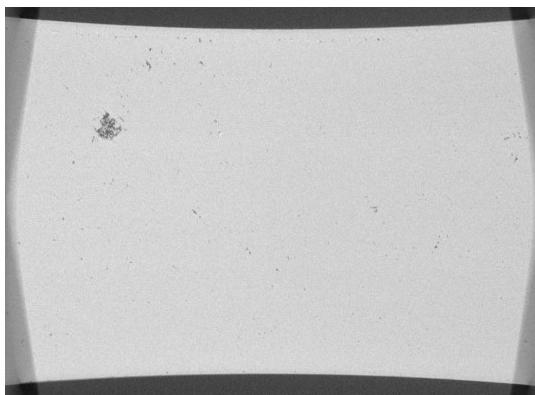
# Registration case #2: additive manufacturing porosity



Fatigue specimen<sup>1</sup>, 3.3 mm thick  
(red box showing X-ray computational tomography (CT) region)



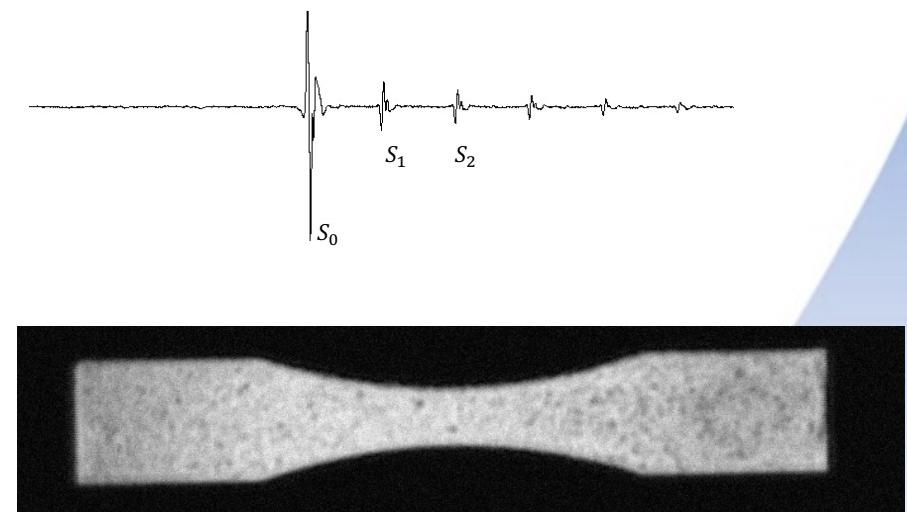
Conceptual sketch of UT pulse-echo NDE



Rescale  
→



Slice from X-ray CT in neck region,  
rescaled to same 0.005" resolution as UT image



Ultrasonic (UT) C-scan of first back-wall reflection  
showing specimen porosity

<sup>1</sup>Additive manufacturing fatigue samples, presented in:  
Yeratapally, Saikumar Reddy, Christopher Lang, and Edward H. Glaessgen. "A computational study to investigate the effect of defect geometries on the fatigue crack driving forces in powder-bed AM materials." *AIAA Scitech 2020 Forum*. 2020.



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# Image registration approach

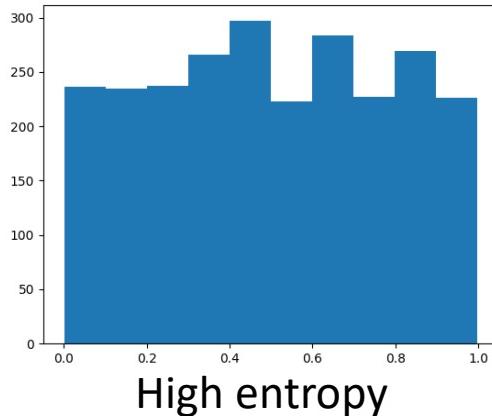
# Normalized mutual information



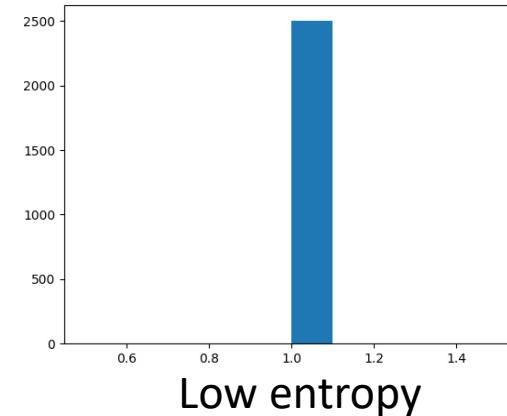
Log-entropy (Shannon information)

$$H(A) = \sum p_i \log \frac{1}{p_i}$$

- $A$  random variable (e.g., image)
- Rare events contribute more information



High entropy

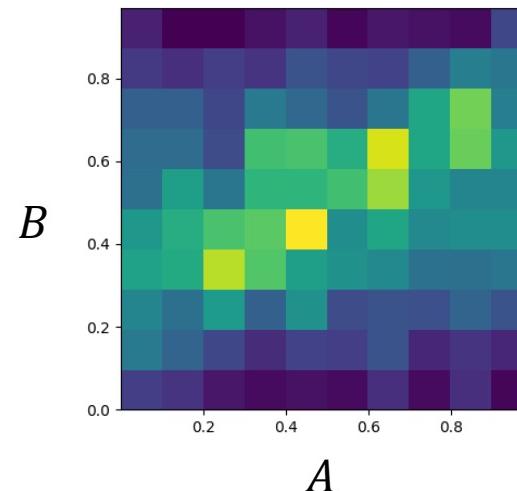


Low entropy

Normalized mutual information<sup>2</sup>

$$Y(A, B) = \frac{H(A) + H(B)}{H(A, B)}$$

- $(A, B)$  joint random variable

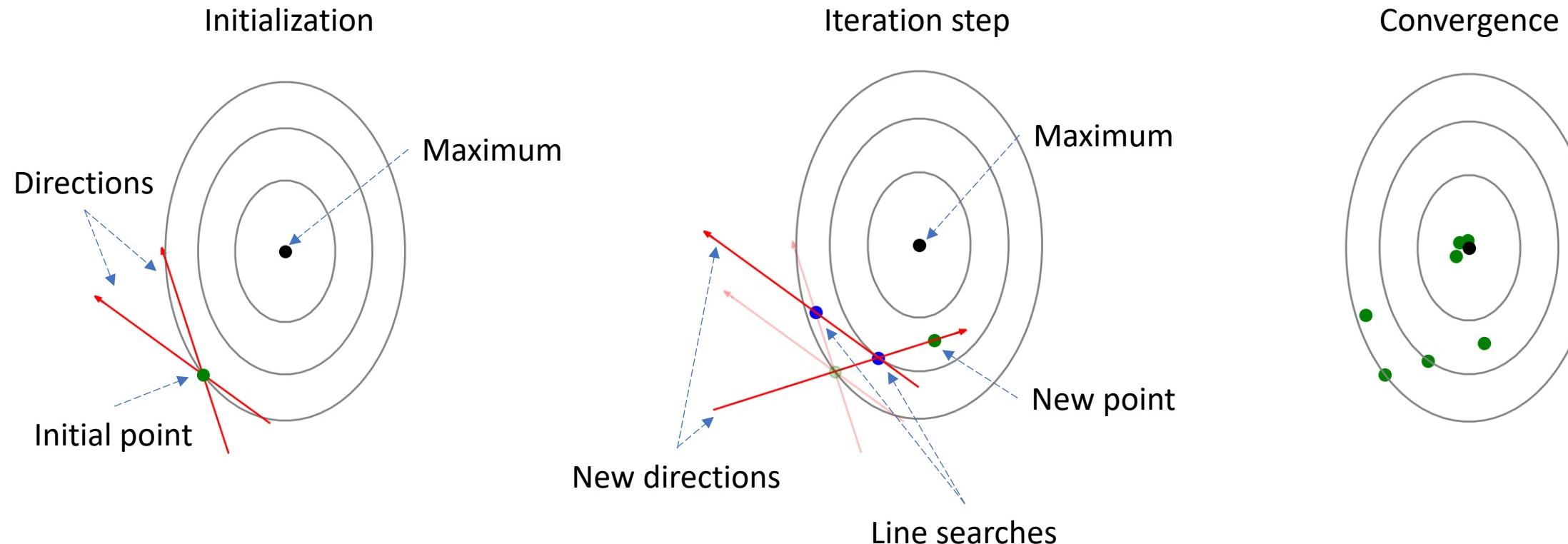


Goal of the registration:  
concentrate the joint  
histogram into the fewest  
number of bins with  
respect to the entropy of  
the overlap.

<sup>2</sup>Normalized Mutual Information introduced in:

C. Studholme, D. Hill and D. Hawkes, "An overlap invariant entropy measure of 3D medical image alignment," Pattern Recognition, vol. 32, no. 1, pp. 71-86, 1999.

# Computing the optimal translation



Formulated as a two-dimensional template matching problem – find the translation that maximizes mutual information

Powell's method<sup>3</sup> for computing the information-maximizing translation:

- Gradient free method
- Quadratically convergent

<sup>3</sup>M. Powell, "An efficient method for finding the minimum of a function of several variables without calculating derivatives," Computer Journal, vol. 7, no. 2, pp. 155-162, 1964.

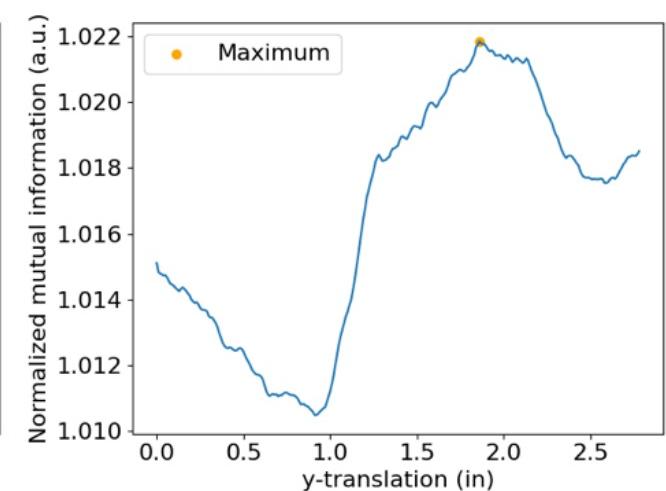
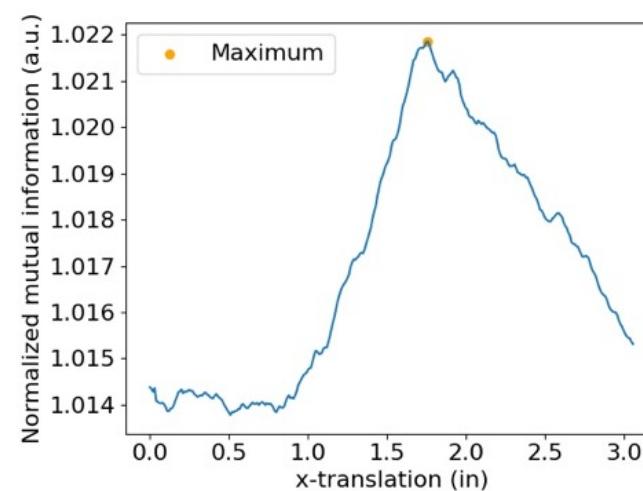
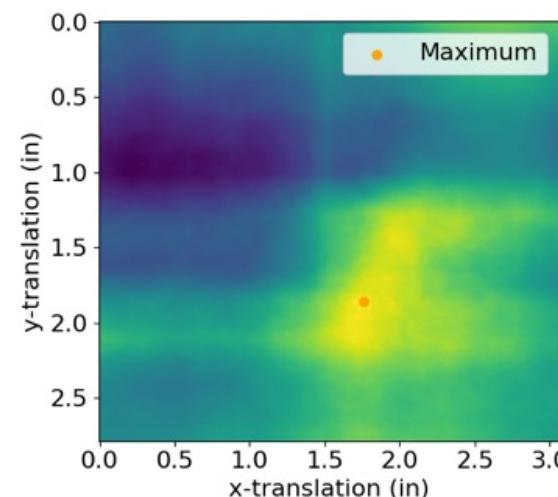
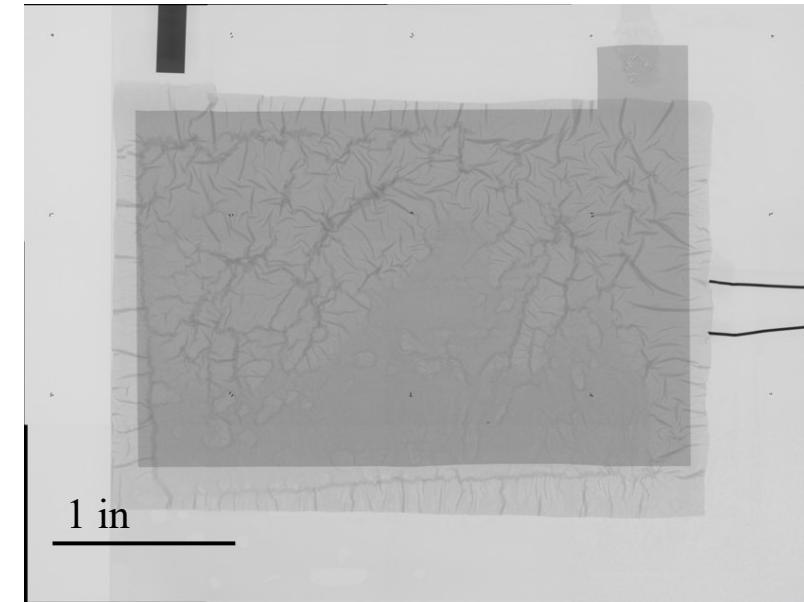
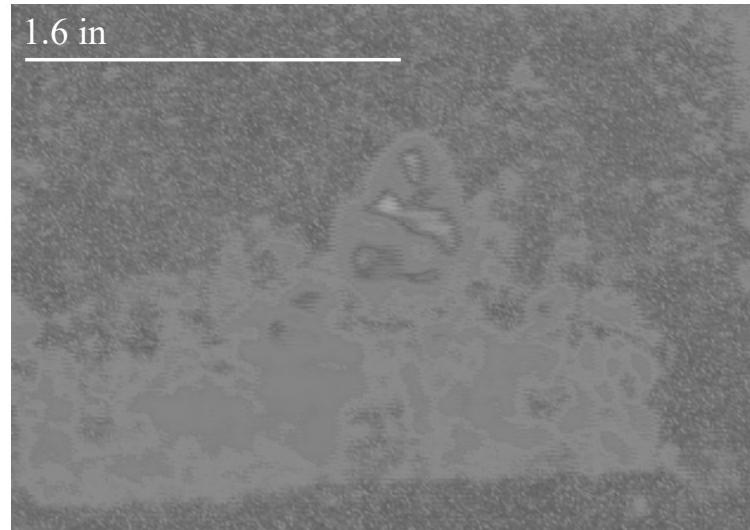


# Image registration results

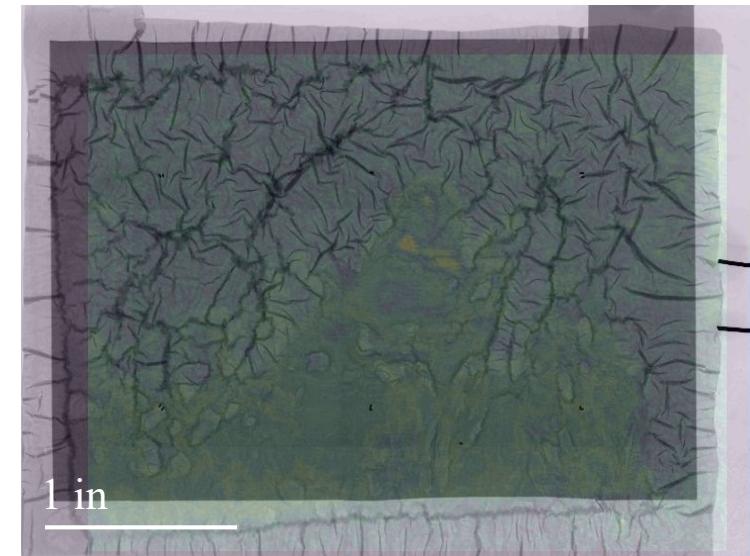
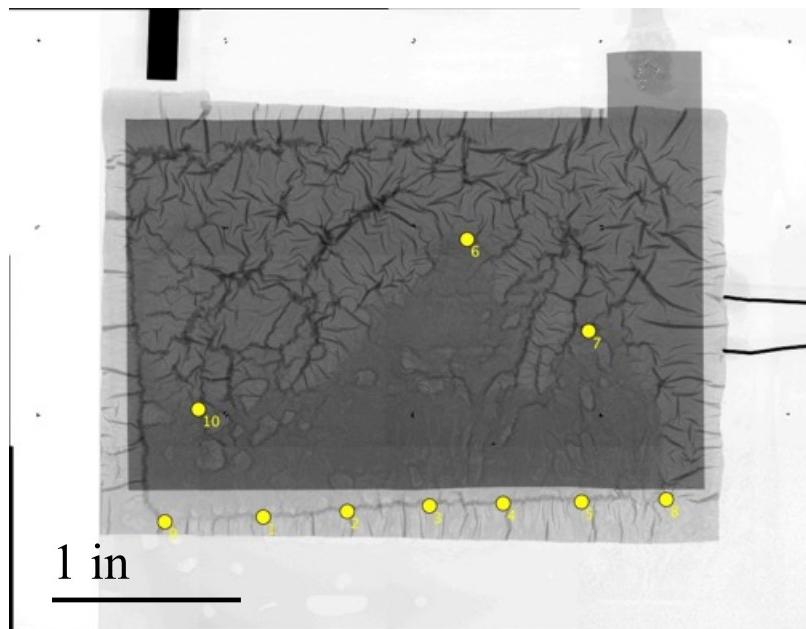
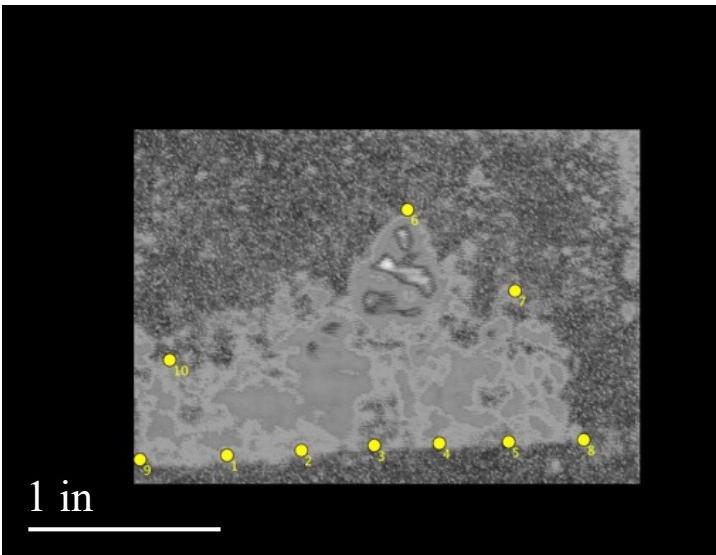
# Li-metal pouch cells



- Lower resolution UT data set mapped into higher resolution digital radiograph DR
- DR is first rescaled to match UT pixel resolution
- Optimal translation of UT into DR selected to optimize normalized mutual information



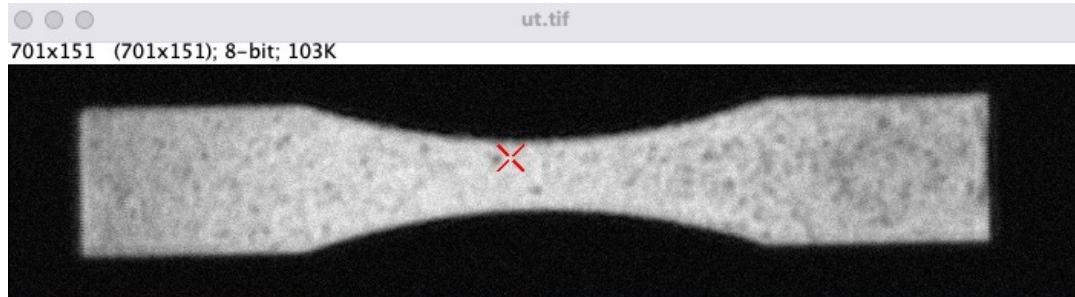
# Comparing the matched images



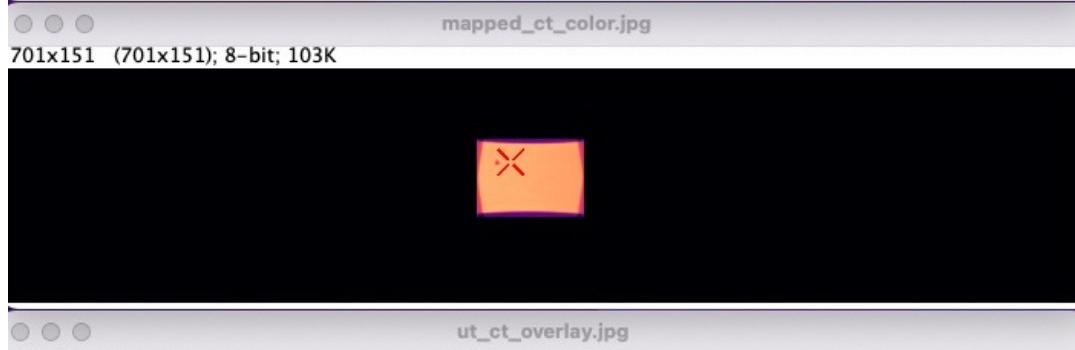
# Additive manufacturing registration results



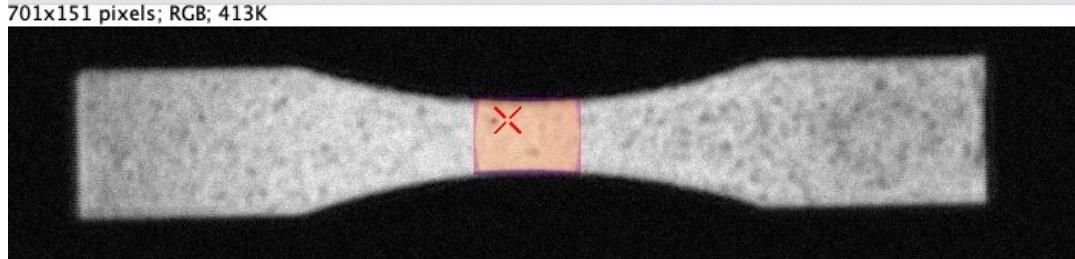
UT



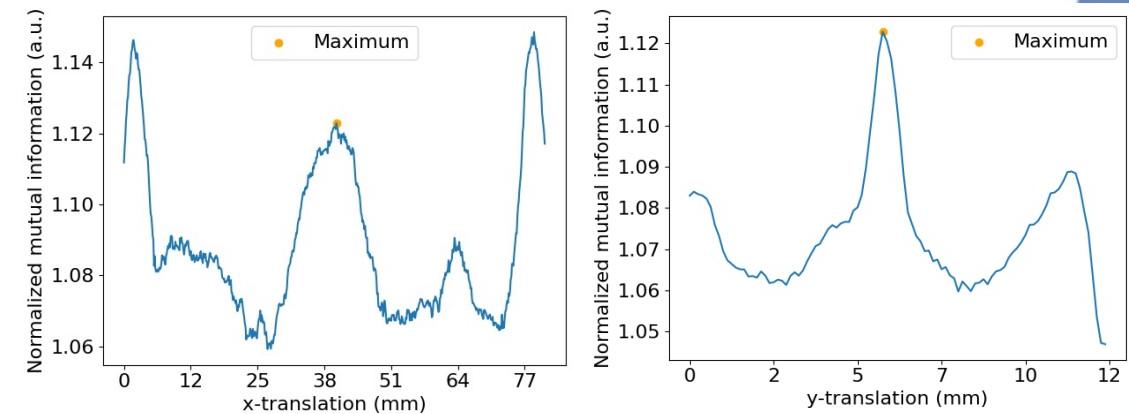
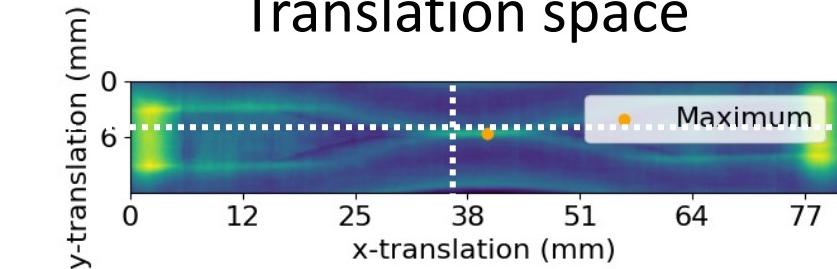
Mapped CT



Overlay



Translation space



A local max occurs at approximately (41mm, 6mm) in translation space

# Accuracy and time-complexity



	Ti-64Al-4V AM coupon	Lithium Metal Pouch Cell
Estimated registration error	0.649 (mm)	0.648 (mm)
	For both cases, global registration produced ~3 pixel local error in landmark locations	

	Computational time	Problem size	Time-complexity estimate $N$
Ti-64Al-4V AM coupon	0.59 (s)	101 pixels by 21 pixels	N/A
Lithium Metal Pouch Cell	13.04 (s)	139 pixels by 153 pixels	1.29
Lithium Metal Pouch Cell	74.19 (s)	307 pixels by 297 pixels	1.35
Lithium Metal Pouch Cell	189.41 (s)	418 pixels by 469 pixels	1.28

$$N \log \frac{n_1}{n_2} = \log \frac{t_1}{t_2}$$

Suggestive of approximately linear relationship between run time and problem size, with total run time feasible for routine registration uses cases

# Conclusions

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- Demonstrates feasibility of mutual information methodology to register images derived from different NDE modalities
  - Radiography to UT NDE registration (and vice versa)
  - Applied to laser powder bed fusion additive manufacturing and Li-metal battery NDE datasets
- For both cases, global registration produced ~3 pixel local error in landmark locations
- Enabler for NDE data fusion methodologies, for combined defect recognition using information from multiple techniques